MEASUREMENT OF KODAIKANAL WHITE-LIGHT IMAGES

I. *A Comparison of 35 Years of Kodaikanal and Mount Wilson Sunspot Data*

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Abstract. A program of digitization of the daily white-light solar images from the Kodaikanal station of the Indian Institute of Astrophysics is in progress. A similar set of white-light data from the Mount Wilson Observatory was digitized some years ago. In both cases, areas and positions of individual sunspot umbrae are measured. In this preliminary report, comparisons of these measurements from the two sites are made. It is shown that both area and position measurements are in quite good agreement. The agreement is sufficiently good that it is possible to measure motions and area changes of sunspots from one site to the next, involving time differences from about 12 hours to about 36 hours. This enables us to trace the motions of many more small sunspots than could be done from one site alone. Very small systematic differences in rotation rate between the two sites of about 0.4% are found. A portion of this discrepancy is apparently due to the difference in plate scales between the two sites. Another contributing factor in the difference is the latitude visibility of sunspots. In addition it is suggested that a small, systematic difference in the measured radii at the two sites may contribute a small amount to this discrepancy, but it has not been possible to confirm this hypothesis. It is concluded that in general, when dealing with high precision rotation results of this sort, one must be extremely careful about subtle systematic effects.

1. Introduction

A program to measure the area and position of each sunspot umbra from the daily photoheliograms of the Kodaikanal station of the Indian Institute of Astrophysics was initiated recently. These photographic data extend back to 1904 in an observational series that continues to the present day. The measurements follow the procedure adopted for the measurement of a similar data set in the interval 1917–1985, done at Mount Wilson several years ago. The instrument, the data set, the method of digitizing, and the first results of the Mount Wilson measurements were discussed in an earlier paper (Howard, Gilman, and Gilman, 1984; herafter HGG).

We intend to compare the results from the two data sets and also to combine the data to obtain a more comprehensive data set of sunspot areas and positions, covering most of this century. We expect several advantages in these combined data. Of course, the Kodaikanal data extend about one activity cycle further back

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than does the Mount Wilson data set. Also the 12-hour time difference between the two sites should make it possible to follow (from one observation to the next at the other site) more small spots than would be possible from any one site because of the short lifetimes of these features. Furthermore, the climate patterns of the two sites are complementary: the winter is the best observing season, in terms of number of clear days, at Kodaikanal and the summer is the worst, while at Mount Wilson the summer is the best season, and the winter is the worst. This factor should significantly increase the total coverage when the data from both sites are combined.

An earlier paper (Howard *et al.*, 1989) discussed the measurements and presented some very preliminary comparisons of the two data sets. Now a substantial fraction of the Kodaikanal measurements have been completed, and in this paper we present the results of some detailed comparisons of measurements at the two sites.

2. The Telescope and the Camera

Direct photography of the Sun commenced at Kodaikanal in August 1903 when the photoheliograph Dallmeyer No. 4 was overhauled and put into operation. This used a 4-inch (10 cm) aperture, 5-foot (1.5 m) focal length objective lens (made by Dallmeyer), modified to give an 8-inch (20 cm) diameter image of the Sun similar to the photoheliographs operated from Dehra Dun (India), Mauritius, and Greenwich. Photography on a systematic, daily basis started in 1904, using this photoheliograph on Lantern plates of size 10 × 10-inches (25.4 × 25.4 cm) and continued until 31 July, 1912. In 1908 the objective lens was replaced by a new one of superior quality. Starting on 31 July, 1912 the direct photography was carried out with the Lerebour and Secretan equatorial telescope having an aperture of 6 inches (15 cm) and a focal length of 8 feet (2.44 m). This, one of the oldest of the Kodaikanal telescopes, was brought to the site in 1898 from Madras and had been used since 1901, with an enlarged 8-inch diameter image, for visual observations of the solar disk. In 1912 the original objective was replaced by John Evershed with a Cooke photo-visual objective of the same aperture, and it was installed in its present location and adapted for direct photography, using an 8-inch diameter solar image in addition to the visual observations. Photography of the Sun continued regularly with this setup until June 1915, when this telescope was dismantled and the objective and auxiliary optical components were moved to Kashmir, where John Evershed used them for solar photography during 1916. The telescope was reinstalled at Kodaikanal and regular observations as before were resumed starting in February 1917. In June 1918, the 6-inch photo-visual lens, used until that time, was replaced by a visual achromat of the same diameter and focal length, and a green filter was also added to the telescope. This gave very good quality images of the Sun, and regular photography was resumed. Since then the photoheliograms have been obtained with this telescope using the same procedures up to the present time.

The camera used to photograph the solar image has a focal plane shutter which is a metal plate in the form of a sector with a filter mount on it for mounting a broad-band filter. The shutter is activated by releasing a metal spring, and the shutter then slides across an aperture, providing an exposure with a duration of about 0.001 s. In 1975 the availability of plates (Ilford special Lantern, 10×10-inch size) became irregular and these were replaced by high-contrast film of the same size.

The plates/films containing the images are stored individually in paper envelopes, and they have been carefully preserved over the years in the plate vault at Kodaikanal under good conditions for preservation of the materials. The observing logs for each day of the observations are also well preserved.

3. Data

For each site, the observational data consist of daily, white-light photographs of the full solar disk. The Kodaikanal images are about 20 cm in diameter, as described above, whereas the Mount Wilson images have a diameter of about 16.5 cm, so the image size (area) of the Kodaikanal observations is larger than that of the Mount Wilson images by nearly 50%. Exposure times are comparable and other features of the observations, notably the average photographic densities, appear to be about the same. Observations at both sites were generally made in the early morning, although in recent decades at Mount Wilson other observations have interfered, and the result has been that many of the daily plates were taken later in the morning, or even in the afternoon. An effect of this change in observing time will be discussed below.

The Kodaikanal data set was started early in 1904, and continues to this date. The Mount Wilson data set started early in 1917, and measurements have been made through the data of 1985, although the observations continue.

The program for measuring the Kodaikanal data is similar to that carried out for the Mount Wilson data: measurements are made in full-year intervals, and the order of the years is random – a different random selection of years than that used for the Mount Wilson data. In a later table in this paper we listed the 35 years for which the Kodaikanal measurements have been completed so far (as of September 1992) and thus for which (after 1916 and before 1986) there are data to compare from the two sites. There are actually a total of 46 years that have been measured to date from this data set, and of these 35 overlap with available Mount Wilson data.

Altogether there are 16568 days of data and 13838 consecutive day pairs in the full (69-year) Mount Wilson data set, and 9712 days of Kodaikanal data with 7924 consecutive day pairs in the full (46-year) data set measured so far. In the overlapping 35 years there were 8057 days and 6689 consecutive day pairs in the Mount Wilson data set and 8046 days with 6635 consecutive day pairs in the Kodaikanal data. In the combined data set for the 35 years of overlapping data there are 16178 'days' of observation and 15563 'consecutive day pairs'.

4. Measurement Technique

The technique of measurement of the umbral areas used in this study was discussed in detail in the earlier paper (HGG). An identical technique is used at Kodaikanal. Each plate is oriented with the axis of rotation along the Y-axis of a digitizing pad. Positions are recorded in the two coordinates of the pad by use of a hand-held cursor. The Mount Wilson plates have pole markers on them, which were exposed using a small mask at the time the image was exposed. The Kodaikanal images have a straight line exposed across them, near disk center, denoting the east–west direction in the sky. This line is formed by a thin wire stretched across the focal plane of the telescope. The Kodaikanal plates are adjusted in orientation angle at the time of the measurement, using the ephemeris P-angle to orient the rotation pole along the Y-axis.

The measurement of each day's plate begins with the digitization of 8 limb points, equally spaced apart. This is done to determine the precise position of the solar disk in the coordinates of the digitizing pad. Then each umbra on the plate is measured with two positions, as described in the earlier paper (HGG). The positional accuracy of the measurements at each site is limited by the seeing, which is generally 1–2 arc sec. The accuracy of the umbral areas varies with the size and shape of the spot, of course. In the earlier work this accuracy for individual spot measurements was estimated to lead to individual random errors of about 30% for small spots, and it is likely that for the more recent measurements approximately the same estimate would apply. The larger plate scale for the Kodaikanal plates should lead to smaller random measurement errors. Possible systematic errors are discussed below.

5. Reduction Technique

The reduction technique is described in the earlier work (HGG). Corrections are made for atmospheric refraction in both the limb solution and the individual umbral area and position determinations. All areas are corrected to disk center.

In practice, the same computer programs are used for the data of both sites for all phases of the reduction, with only some necessary differences between the sites included (such as the site latitude, which is needed in the determination of the altitude of each measurement, which in turn is needed for the calculation of the atmospheric refraction correction).

The result of this first phase of the analysis is a list of umbral areas, positions, dates, and times of observation. The second step is to combine data from adjacent days. In the case of observations from one site only, we can simply use the date to determine whether an observation is from the next day or not. When we combine the data from two sites, we use the date and time, and define the 'next day' to

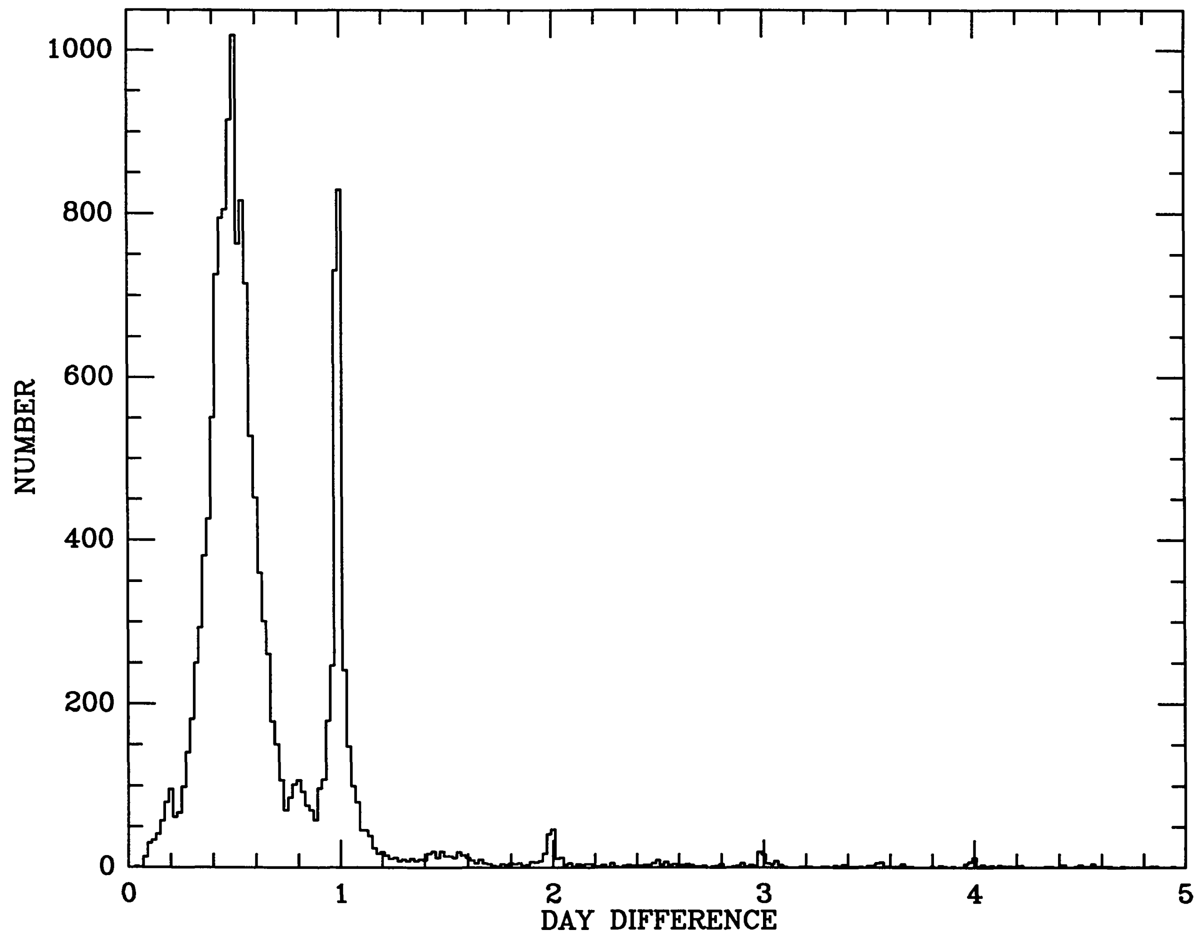

Fig. 1. Distribution of time differences (in days) between the data at the two sites. The 35-year, two-site data set was used to compute these differences.

be the next observation (from either site) which falls within some time interval. This interval has been chosen arbitrarily to be 1.8 days (43.2 hours) from the first observation. This interval was chosen to include all the $1\frac{1}{2}$-day differences, judging from Figure 1. If there is no observation at either site that falls within this time interval, then, by definition, we do not have two 'consecutive days'.

Figure 1 shows a plot of time differences between 'consecutive days' for the combined data set from the two sites (35 years of data). This is shown to illustrate the relatively large number of 12-hour 'returns' that are found in the combined data set. Clearly the biggest peak falls near 12 hours. The second biggest peak is centered on 24 hours, and this represents pairs of observations from the same site. Much smaller peaks may be seen at 12-hour intervals for several days. The rather broad width of the 12- and 36-hour peaks is due to the fact that there is a wide range of times of observations at the two sites. This is particularly true at Mount Wilson, where, as mentioned above, recently other observations have interfered with the cadence of the white-light photographs. If one plots individual years in the same way as Figure 1 is plotted, one sees for the early years a rather narrow peak at 12 and even 36 hours. In later years, in plots similar to Figure 1, there is a tendency to see a double peak centered near these two times, one corresponding to Mount Wilson observations made early in the day and one corresponding to Mount Wilson observations made late in the day.

Rotation rates are determined, as in the earlier work (HGG), by dividing the longitude difference of the group or of each individual sunspot within the group by the time difference between the two observations. One would expect therefore that random measurement errors would lead to somewhat larger random errors in rotation determinations for the combined data set than for the data set from either site, because the time differences are shorter on average for the combined set. Note, however, that errors in longitude measurement of this sort do not result in random, independent errors in the average rotation rates. This is because an error in one longitude in a string of such measurements will increase the derived rotation rate on one side and decrease it on the other side, so that the average will be relatively unaffected (Howard, 1992). This means that we may expect that to some extent the errors derived for the rotation rates from these data will be overestimated. In addition, of course, for the combined data set, the larger number of days of observation will lower the errors below those derived from the individual sites.

6. Area Comparisons

Table I gives daily, full-disk sunspot umbral areas, in μhemisphere, averaged over $\frac{1}{12}$ of a year and full years for both sites for the 35 years for which there is overlapping data. One would not expect perfect agreement between these results from the two sites because the coverage is rarely exactly the same, i.e., rarely in a month (and never in a year) is exactly the same set of days covered in both data sets. Nevertheless, the agreement is encouragingly good. Generally active months are seen as such at both sites. (Note that these results for Mount Wilson are not identical to a similar table given in the earlier paper (HGG). The reason for this is that over the years a number of small improvements have been made to the software, which has resulted in identifying generally a somewhat greater number of sunspots from these observations than was done before.)

It can be seen in Table I, however, that generally, although not for all months or years, the Kodaikanal daily spot areas are larger than those from the Mount Wilson plates. This result will be discussed in more detail in what follows.

In the full (69-year) Mount Wilson data set there were a total of 366680 sunspots measured on 13838 day pairs, and of these 111070 were identified as the same spot (a 'return') on the next day. Using just the overlapping 35 years, the Mount Wilson spot measurements on 6689 consecutive day pairs numbered 180667, and of this total, 55357 spots were measured as returns. In the same set of Kodaikanal years 188408 spots were measured on 6635 consecutive day pairs, and of this total, 70178 spots returned. For the full 46 years measured so far at Kodaikanal, the numbers are 77527 returns out of 209006 spots. In the 35-year combined data set, there were a total of 421678 spots, out of which 74372 spots returned in 15563 'day pairs'. (Note here that 'spots' means spots measured on a single day. One spot may be counted more than once as it rotates across the solar disk.)

From these numbers, several conclusions may be drawn. To begin with, there are about 5% more spots measured per day on the Kodaikanal plates than on the Mount Wilson plates. This, we believe, is due to the larger image scale for the Kodaikanal observations. We are seeing a greater number of smaller spots in this data set. It is possible also that systematic seeing differences between the two sites may play a role in this comparison, but it is impossible to quantify this effect. It is known that both sites are quite good seeing sites, but beyond that we cannot determine quantitatively any differences without experiments that are beyond the scope of this study.

Another conclusion from the results cited above is that there is a greater fraction of returns seen on the Kodaikanal plates ($\approx$ 0.37) than on the Mount Wilson plates ($\approx$ 0.31). This is most likely due firstly to the fact that, as mentioned above, more small spots are seen at Kodaikanal, and thus it is more likely that spots can be followed longer as they decay to a smaller size, and, secondly, that more spots measured means that better group positions are determined, and thus, since individual spot returns are determined from the relative positions of spots within groups on two consecutive days (HGG), better identifications of individual spot returns can be made. Note that the fraction of returns for the combined data set ($\approx$0.41) is greater than that for either site reduced separately. This undoubtedly results from the fact that with a shorter time base more short-lived spots can be traced from one observation to the next.

As one means of testing this explanation for the presence of more spots at Kodaikanal than at Mount Wilson, we have examined the distribution of spot sizes at the two sites. Table II gives the distributions and relative distributions of sunspot counts in various size categories at the two sites.

These data come from the 35-year overlapping data set for the two sites, and they represent the total number of spots measured, not the number that were identified as returns or even the number seen on consecutive days. Thus the number of spots is larger than that discussed elsewhere in this paper. It may be seen that the largest differences and the largest percentage differences are seen at the smallest spot sizes, which is what one would expect because of the difference in image scales. It should be remembered that at both sites, for the smallest spots, comparable to the size of the cross-hair, the measurer did not attempt to measure the size of the spot in the usual manner, but instead placed the cross-hair centered on the spot and entered two identical positions into the computer. Such small spots were arbitrarily assigned an area of 0.05 μhemisphere (HGG).

We consider that Table II represents a very satisfactory agreement between the area measurements at the two sites, considering the image-scale differences mentioned above. Except for the smallest spots, the distributions agree within a few tenths of a percent. These area distributions compare well with a recent detailed

TABLE I

Average daily sunspot areas for the two sites (μ hemisphere)

Year	1	2	3	4	5	6	7	8	9	10	11	12	Full year
1917													
Kodai	258.7	80.1	92.4	89.3	110.9	104.0	113.2	169.8	142.6	57.7	93.1	167.8	111.9
Mt. W.	52.4	92.8	81.8	76.3	105.2	89.3	103.6	214.4	136.0	63.4	96.9	147.6	107.4
1918													
Kodai	108.7	40.7	60.8	68.5	50.1	73.1	93.2	97.0	60.7	69.8	54.3	59.0	67.9
Mt. W.	91.9	48.3	62.1	70.0	65.5	41.1	89.5	106.7	62.9	67.1	48.6	40.2	67.9
1922													
Kodai	7.0	53.6	101.8	17.7	10.4	5.4	18.0	13.4	3.1	7.0	6.1	74.6	35.7
Mt. W.	3.3	42.7	56.3	13.3	8.5	4.3	8.7	14.8	6.2	7.2	1.7	40.5	21.5
1923													
Kodai	21.0	1.5	5.3	3.0	2.7	5.3	0.3	2.4	3.9	2.9	6.5	3.9	5.0
Mt. W.	16.8	0.1	6.7	1.5	2.6	7.3	1.6	4.4	2.5	3.1	5.1	0.5	4.1
1924													
Kodai	2.8	32.2	8.3	42.1	17.6	30.3	31.7	27.1	24.1	28.6	68.7	22.3	30.5
Mt. W.	0.7	17.5	2.4	24.9	14.7	23.3	20.1	14.9	16.6	16.2	35.0	10.8	18.6
1928													
Kodai	117.8	65.6	92.4	76.8	68.3	86.5	111.7	64.8	114.1	63.4	28.1	60.9	81.3
Mt. W.	100.0	67.1	93.9	70.9	55.9	67.4	103.1	65.0	117.7	47.4	29.0	36.2	74.3
1932													
Kodai	9.1	16.7	6.4	15.3	18.0	17.7	5.9	8.7	0.2	5.2	9.7	17.7	12.4
Mt. W.	8.3	21.8	5.8	12.9	12.9	17.4	4.8	3.6	0.2	5.2	11.5	11.8	10.7
1933													
Kodai	11.8	70.2	10.0	3.6	1.4	2.3	1.8	0.0	2.8	13.3	0.0	0.0	19.0
Mt. W.	17.5	68.5	15.6	0.7	2.4	5.3	0.0	0.0	9.5	13.8	0.0	3.3	20.1
1935													
Kodai	14.6	14.2	18.6	11.7	33.1	42.5	32.8	22.8	34.3	58.8	102.9	147.5	40.0
Mt. W.	23.0	7.1	15.5	10.9	34.4	39.3	29.4	19.5	30.2	51.6	85.4	83.2	37.6

Table I (continued)

Year	1	2	3	4	5	6	7	8	9	10	11	12	Full year
1938													
Kodai	169.6	123.3	112.4	171.2	172.6	106.3	216.6	116.9	79.5	89.8	163.0	128.7	138.0
Mt. W.	112.8	88.2	81.9	124.7	135.7	101.9	176.3	113.0	79.6	87.9	137.8	75.0	115.0
1940													
Kodai	78.9	67.3	107.7	42.9	56.0	96.7	64.2	133.2	76.0	52.5	41.2	67.7	73.9
Mt. W.	49.8	49.4	77.4	36.4	49.6	78.1	61.2	103.6	58.4	52.5	37.3	46.8	58.3
1943													
Kodai	7.8	48.2	46.4	49.5	4.9	4.0	17.2	8.0	16.3	21.4	11.6	29.7	26.0
Mt. W.	4.6	40.6	36.3	46.3	15.0	3.6	23.7	5.3	22.1	30.7	13.7	18.9	22.4
1944													
Kodai	2.2	0.0	22.8	0.0	1.0	0.0	18.1	10.4	26.6	12.2	15.2	52.8	19.1
Mt. W.	1.6	0.0	0.0	6.7	1.4	2.7	5.4	9.7	21.8	11.0	9.2	45.2	15.9
1947													
Kodai	199.4	156.8	237.5	229.9	230.9	137.1	161.5	187.8	125.0	134.0	82.1	137.4	166.4
Mt. W.	139.3	141.8	206.5	192.6	183.3	104.0	164.0	210.8	180.0	163.7	110.3	139.3	161.5
1948													
Kodai	105.5	93.5	127.1	275.4	229.6	189.1	170.5	178.3	121.8	112.5	76.4	162.0	153.4
Mt. W.	76.9	56.8	103.8	234.0	193.3	156.9	139.8	130.6	113.7	92.8	48.4	121.4	102.2
1949													
Kodai	144.5	287.3	259.2	150.0	93.1	107.5	157.0	139.9	143.2	122.0	160.8	100.7	158.1
Mt. W.	86.8	198.3	184.5	108.3	98.4	105.3	111.1	128.8	122.2	159.3	129.9	82.3	125.5
1950													
Kodai	88.9	120.3	104.9	153.3	74.0	65.5	52.0	61.0	36.7	30.0	43.1	34.1	76.0
Mt. W.	69.4	122.3	104.6	163.7	99.9	70.1	83.8	70.1	28.0	34.5	44.8	46.5	82.5
1951													
Kodai	62.4	36.1	59.0	107.7	246.7	133.2	37.4	48.3	77.0	43.1	38.4	44.9	80.3
Mt. W.	39.7	25.1	55.2	105.7	176.2	126.3	49.3	54.7	61.6	38.0	33.1	30.7	70.2

Table I (continued)

Year	1	2	3	4	5	6	7	8	9	10	11	12	Full year
1952													
Kodai	33.4	48.6	25.0	29.9	28.5	37.7	33.0	49.6	27.6	19.8	32.8	44.0	33.7
Mt. W.	13.1	14.8	17.3	13.3	14.6	33.9	38.7	45.5	22.2	20.6	29.0	26.0	25.2
1953													
Kodai	23.1	0.0	22.7	83.6	6.7	17.6	15.0	33.1	9.1	6.9	0.6	4.4	25.7
Mt. W.	13.1	1.1	7.2	19.5	7.0	10.9	12.5	24.0	11.1	4.7	0.0	3.3	12.0
1957													
Kodai	174.7	116.7	129.6	115.3	223.0	345.2	224.9	179.6	367.3	398.9	237.1	291.3	223.0
Mt. W.	160.2	99.8	100.0	125.2	154.2	304.3	213.6	182.6	338.5	309.4	194.3	298.3	208.1
1959													
Kodai	301.8	141.8	248.5	125.6	148.0	147.7	155.5	152.3	97.4	65.3	129.7	129.0	160.8
Mt. W.	266.3	118.1	231.0	133.4	157.2	184.8	159.8	186.0	109.8	92.3	110.0	125.9	185.5
1960													
Kodai	140.3	100.7	67.4	107.4	98.4	79.6	79.1	148.7	103.8	76.2	49.6	59.7	93.7
Mt. W.	121.5	86.3	72.7	115.5	103.6	85.8	101.3	110.5	82.9	58.3	85.3	43.0	88.1
1963													
Kodai	19.8	11.7	7.5	33.9	29.0	19.3	11.5	20.2	53.5	33.8	11.8	3.0	22.7
Mt. W.	19.0	22.7	0.0	0.0	0.0	0.0	12.2	16.4	36.8	27.2	6.7	4.3	18.3
1965													
Kodai	10.7	2.8	7.0	4.8	22.4	12.5	9.5	5.1	9.0	8.7	16.9	12.8	10.3
Mt. W.	9.1	3.5	4.5	3.6	26.0	11.3	8.6	3.5	12.3	9.9	11.8	9.1	9.2
1966													
Kodai	17.7	16.2	58.4	59.4	31.3	23.3	50.2	31.4	79.5	44.5	51.9	77.6	45.9
Mt. W.	20.6	23.2	55.3	57.5	39.2	29.2	64.5	48.4	71.5	40.7	54.8	115.6	50.5
1968													
Kodai	123.3	97.6	68.6	67.7	127.3	113.8	78.3	102.5	75.0	86.9	66.1	104.2	92.9
Mt. W.	103.6	93.0	70.3	53.5	105.1	95.2	80.6	77.0	71.9	81.6	58.4	84.5	80.3

Table I (continued)

Year	1	2	3	4	5	6	7	8	9	10	11	12	Full year
1973													
Kodai	40.0	23.4	55.3	45.3	25.5	23.3	7.0	22.9	75.7	29.1	19.7	53.3	36.2
Mt. W.	24.1	32.0	52.3	57.2	33.5	29.9	26.0	29.5	71.9	25.2	34.9	17.6	38.3
1974													
Kodai	19.5	27.9	6.5	50.7	48.9	41.8	45.7	29.7	69.4	64.8	25.3	28.6	37.8
Mt. W.	30.6	31.3	9.1	45.5	25.5	29.5	54.3	28.6	56.1	60.2	12.4	22.7	36.2
1975													
Kodai	15.0	9.2	8.4	8.4	18.1	12.1	22.7	83.9	2.2	4.4	20.7	6.4	17.3
Mt. W.	14.1	15.7	22.7	12.2	18.1	29.5	35.2	76.8	4.4	13.8	29.1	17.4	28.6
1976													
Kodai	11.4	2.9	34.8	28.2	3.8	10.1	1.0	16.8	9.0	13.1	1.5	13.6	15.5
Mt. W.	18.5	3.2	33.2	12.7	3.9	8.2	1.1	17.5	9.1	15.0	6.1	11.4	14.2
1977													
Kodai	14.4	19.4	2.6	10.5	16.1	54.0	15.0	18.6	48.1	44.8	20.0	56.8	27.9
Mt. W.	16.1	19.1	5.5	8.0	13.1	31.9	12.1	20.5	37.4	32.7	15.4	47.1	23.7
1981													
Kodai	105.4	221.2	192.1	254.7	188.4	126.0	240.1	241.4	246.1	387.1	161.7	257.2	208.8
Mt. W.	59.1	123.8	106.5	153.5	109.6	79.0	159.5	230.4	156.3	143.5	53.7	143.9	136.5
1982													
Kodai	103.2	223.5	215.4	111.2	71.9	133.1	50.6	140.5	99.9	92.2	105.2	171.5	137.9
Mt. W.	124.2	161.4	162.7	106.5	72.2	156.3	104.6	137.3	88.8	54.6	51.5	135.2	112.9
1984													
Kodai	91.3	138.3	80.9	146.6	98.5	33.4	17.6	11.6	20.2	6.6	15.8	7.6	70.6
Mt. W.	90.7	89.4	56.3	79.3	69.7	32.2	19.4	12.5	13.9	3.6	9.9	5.0	43.5

TABLE II

Sunspot area distributions

Area	Mount Wilson		Kodaikanal	
μhemisphere	Number	%	Number	%
0–1	106146	51.0	108287	49.1
1–2	28503	13.7	32044	14.5
2–3	16842	8.1	19692	8.9
3–4	11508	5.5	13533	6.1
4–5	8296	4.0	9463	4.3
5–6	6268	3.0	6914	3.1
6–7	4888	2.4	5083	2.3
7–8	3995	1.9	3952	1.8
8–9	3054	1.5	3085	1.4
9–10	2588	1.2	2364	1.1
10–11	2023	1.0	1908	0.9
11–12	1688	0.8	1557	0.7
12–13	1416	0.7	1352	0.6
13–14	1210	0.6	1082	0.5
14–15	988	0.5	956	0.4
15–16	882	0.4	869	0.4
16–17	804	0.4	745	0.3
17–18	653	0.3	594	0.3
18–19	599	0.3	538	0.2
19–20	506	0.2	500	0.2
20–21	465	0.2	461	0.2
21–22	423	0.2	389	0.2
22–23	311	0.2	349	0.2
23–24	325	0.2	312	0.1
24–25	274	0.1	323	0.2
>25	3287	1.6	3994	1.8
Total	207942	100.0	220346	100.0

study, using the Mount Wilson data (Bogdan *et al.*, 1988). Figure 2 shows the distribution of the areas for the data from each site. Note that in these comparisons, we are not in all cases comparing images from the same days. Seasonal differences in coverage undoubtedly affect the spot size differences, both in this figure and in the tables in this paper, especially for the largest spots, which are few in number, and perhaps also to some extent for the rotation rate comparisons discussed below.

In order to test this proposed explanation (sampling differences) for the spot size differences, we chose seven years near five different activity maxima and examined in detail the numbers of spots with areas greater than 40 μhemisphere.

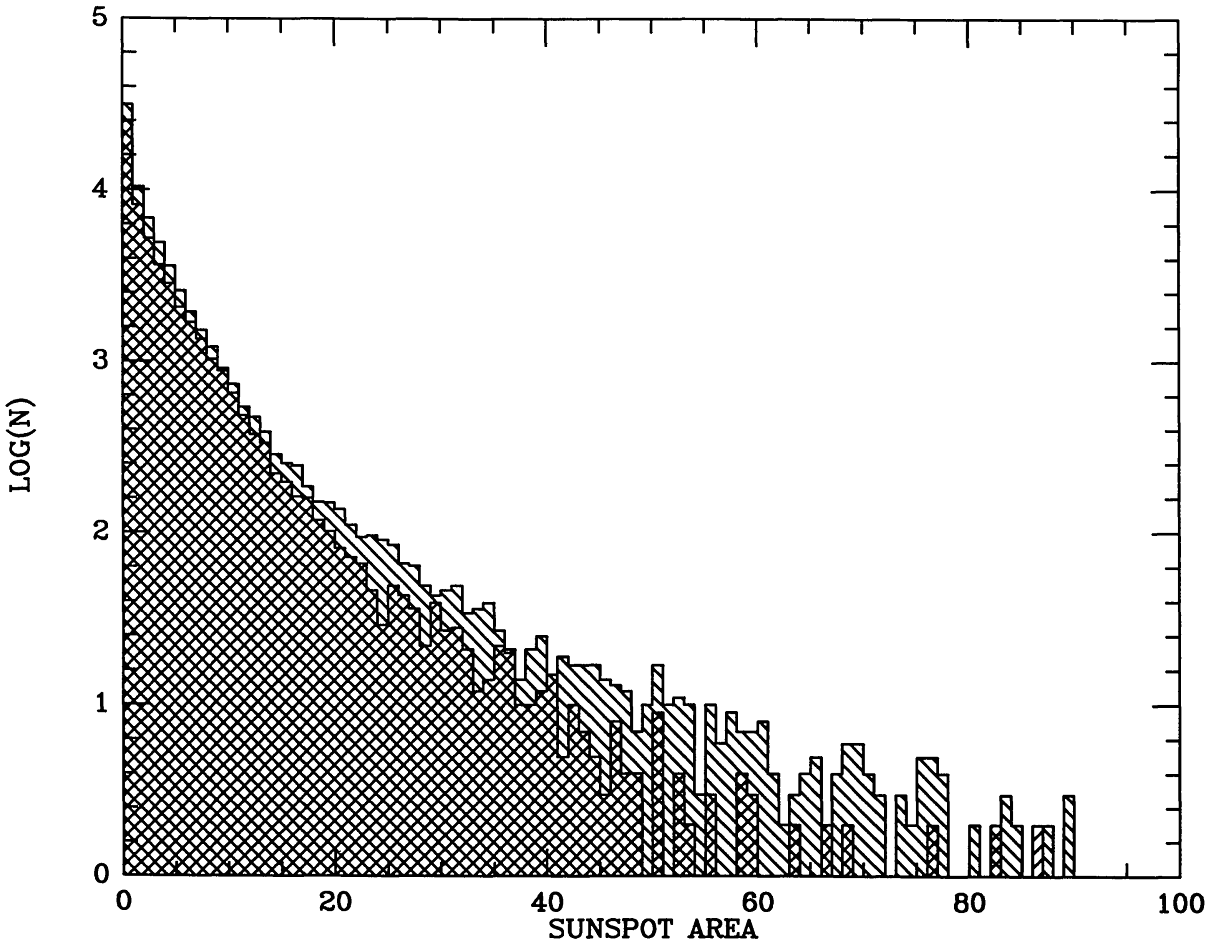

Fig. 2. Histograms of the distribution of sunspots by area (in μhemisphere). The two identical 35-year data sets are used for this plot. The lower, hatched curve represents the Mount Wilson data, and the upper curve is the Kodaikanal data.

These seven years represent a substantial fraction of the large spots seen in this data set. In these years there were 744 such spots measured on the Kodaikanal plates and 463 such spots measured on the Mount Wilson plates. Altogether 188 of these large spots were observed at both sites on the same days. Five-hundred forty of the spots were measured at Kodaikanal on days when there were no observations at Mount Wilson, and 259 of the spots were measured on the Mount Wilson plates on days when there were no observations at Kodaikanal. Only a few percent of the large spots were missed at either site in the measurement process, judging from a comparison with the sunspot drawings in *Solar Geophysical Data*, and many of these are likely to be spots which developed between when the photographs were taken and when the drawings were made. Thus statistical fluctuations account for the differences in the numbers of large sunspots measured at the two sites.

TABLE III

Sunspot sidereal rotation rates by latitude zone, data set, and site

Latitude	<−30	−30−25	−25−20	−20−15	−15−10	−10−5	−05−00	+00+05	+05+10	+10+15	+15+20	+20+25	+25+30	>+30
35 years														
Kodai rate	13.73	14.03	14.19	14.37	14.47	14.56	14.59	14.62	14.54	14.41	14.30	14.13	14.01	13.74
St. dev.	0.034	0.020	0.012	0.009	0.007	0.009	0.016	0.014	0.007	0.006	0.008	0.010	0.016	0.029
No. of spots	627	1551	3503	6831	9600	6907	1908	2691	8615	11543	7806	5615	2363	617
Mt W. rate	13.68	13.92	14.12	14.29	14.38	14.53	14.60	14.53	14.46	14.37	14.25	14.13	14.00	13.75
St. dev.	0.043	0.027	0.017	0.012	0.010	0.011	0.020	0.020	0.011	0.009	0.011	0.014	0.024	0.044
No. of spots	477	1140	2940	5785	7276	6429	1892	1822	6330	9212	6088	3858	1567	538
Both sites	13.90	14.10	14.25	14.44	14.49	14.62	14.67	14.59	14.55	14.47	14.35	14.24	14.18	13.92
St. dev.	0.058	0.031	0.021	0.015	0.011	0.013	0.025	0.022	0.012	0.010	0.013	0.016	0.028	0.054
No. of spots	507	1390	3233	6369	8741	6782	2004	2277	8193	11807	7960	5162	1989	515
46 years														
Kodai rate	13.74	14.04	14.20	14.36	14.46	14.56	14.58	14.63	14.54	14.41	14.30	14.13	14.02	13.73
St. dev.	0.033	0.020	0.012	0.008	0.007	0.008	0.015	0.013	0.007	0.006	0.008	0.009	0.015	0.029
No. of spots	663	1675	3974	7763	10605	7710	2237	2962	9722	12615	8471	6042	2460	627

7. Rotation Comparisons

Table III shows average rotation rates in deg day^{-1} sidereal for individual sunspots in 5-deg latitude zones for the overlapping 35-year data sets for Kodaikanal, Mount Wilson, and the combined data set. For each latitude zone the standard deviation of the mean is listed from the determination of the mean rate in that zone, as well as the number of spots that were measured in each zone. Also given here is the same set of results for the full 46-year data set that is available for the Kodaikanal data. We have also determined the coefficients A and B in the expression $\omega = A + B \sin^2 \phi$ deg day^{-1}, where ϕ is the latitude. These solutions were determined for all the individual spots, not using the average latitude zones. For the 35-year Kodaikanal data, $A = 14.591 \pm 0.004$ and $B = -2.92 \pm 0.042$. For the same years, the Mount Wilson result is $A = 14.533 \pm 0.006$ and $B = -2.87 \pm 0.071$. For the combined data set, $A = 14.610 \pm 0.007$ and $B = -2.448 \pm 0.070$. For the 46-year data set, the Kodaikanal results are: $A = 14.589 \pm 0.004$ and $B = -2.90 \pm 0.04$.

It is clear that the average sunspot rotation rate is greater by about 0.4% ($\approx$ 8 m s^{-1} at the equator) for the Kodaikanal data than for the Mount Wilson data. This is obtained from the equatorial rates listed above. This is a small difference, of course, nevertheless it is a significant difference, as may be judged from the errors – which as noted above are likely to be overestimated – and from Figure 3, which compares the latitude dependence of the rotation rate at the two sites, using the 35-year data sets. This difference could be due to the fact that, as discussed above, more smaller spots are measured in the Kodaikanal data set, and, as has been determined previously, smaller spots rotate faster than larger spots (HGG).

In order to investigate this possibility further, and also in order to examine the possibility that there are small systematic differences in the measuring technique between the two measurers that might lead to systematic differences in the measured areas of some or all sunspots at the two sites, we have examined the rotation rate of spots as a function of spot size from the two data sets. Figure 4 shows a plot of average rotation rates for sunspots averaged over area bins of 1 μhemisphere. It can be seen in Figure 4 that the Kodaikanal rotation rates are significantly faster than the Mount Wilson rates in the interval 2–8 μhemisphere by roughly 0.05 deg day^{-1}, or about 0.3%. Curiously, the rotation rates of the smallest (1 μhemisphere) spots are quite close.

Judging from the relative area distributions of Table II and the rotation rate distributions of Figure 4, one can estimate that the rate differences seen in Figure 4 will affect the average rotation rates at the two sites by enough to account for a rotation rate difference of 0.18% between the two sites. This was done by weighting the rotation rates at each area bin by the number of spots in that bin at the other site and deriving an average rate for each site from these weighted quantities. This may still leave about half the rotation rate difference between the two sites unaccounted for. This appears to be well within the errors of measurement, although, as discussed above, these errors are overestimates.

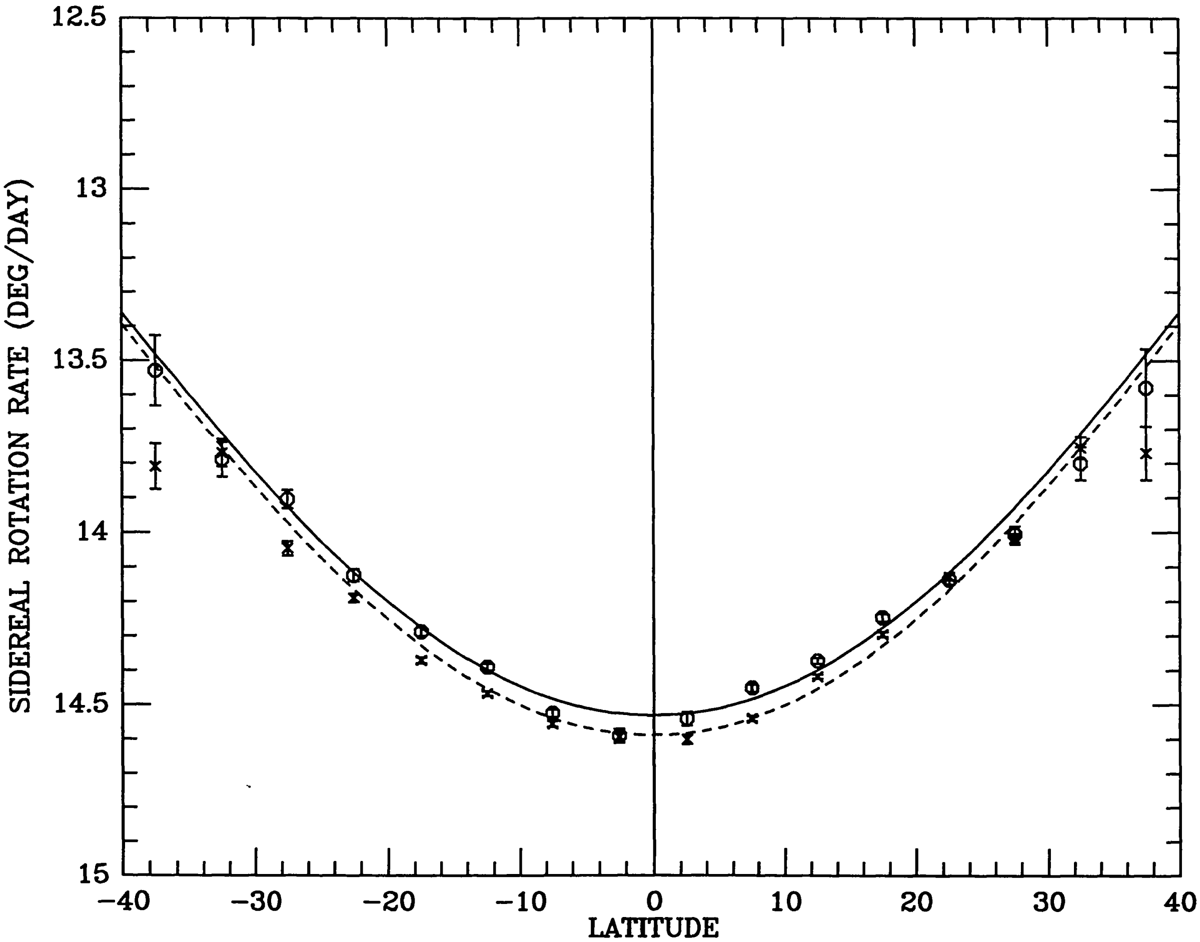

Fig. 3. Rotation rate in deg day^{-1} averaged over 5-deg bins of latitude for Mount Wilson (solid lines) and Kodaikanal (dashed lines) data. The identical 35-year data sets are used for this plot. Full error bars for this and the remaining figures are two standard errors. (For many of the points here the error bars are smaller than the points.)

Another possible cause for systematic rotation rate differences between the two sites is a systematic difference in the radius determinations. This results from the projection from the plane of the photographic plate to coordinates on the solar surface. Such an error in the measured radius could be caused by slightly different techniques used by the two measurers, for example. But this seems a bit unlikely. In order to account for the full measured difference in rotation rate, the systematic difference in radius would have to be 2 arc sec. This is larger than the average seeing effect at either site, and corresponds to about 0.2 mm on the plates. It is possible, however, that systematic differences in this quantity do exist and affect the rotation results at some level.

It is possible to estimate the effect of radius error on the rotation rate by examining the rotation rate derived at various central meridian distances (CMDs). Because of projection effects, the effects of radius errors on measured rotation rates will be greater at greater distances from the central meridian. Figure 5 shows average rotation rates for various CMD values. This was done for umbral areas

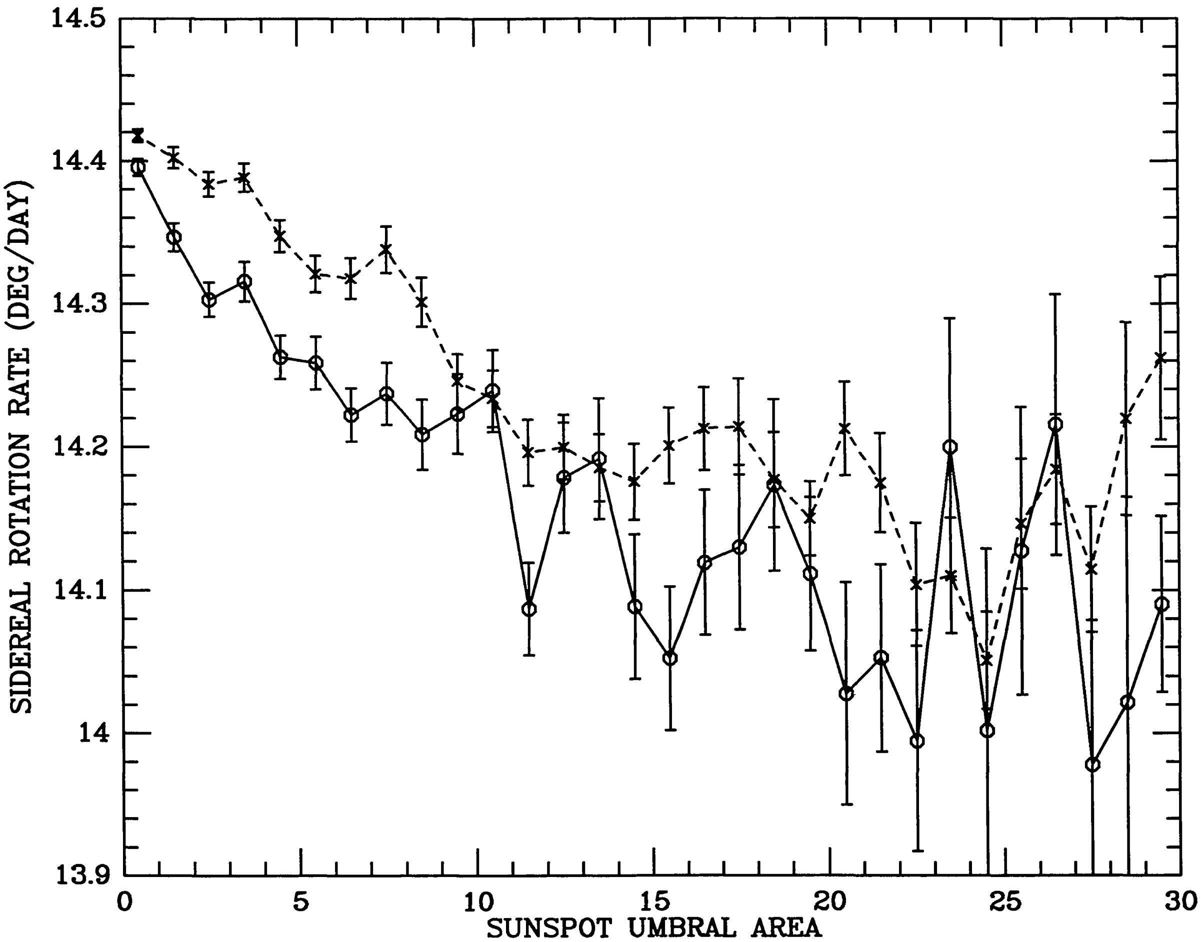

Fig. 4. Average rotation rates for spots in area bins of 1 μhemisphere. Circles and solid lines represent the 35-year Mount Wilson data set, and the $\times$'s and dashed lines represent the same years in the Kodaikanal data.

<1 μhemisphere only in order to avoid the effects of varying visibility of sunspots at different CMD values combined with the faster rotation shown by smaller sunspots. Clearly there is little or no significant effect here. Linear least-squares solutions for the points that go into Figure 5 give identical slopes for the two data sets (+0.0003), but the errors in each case are nearly the same as the slopes. Shown for reference are two modelled results (from a simple geometrical model of the projection of coordinates on a sphere) for a 0.1% and 0.2% error in radius – a radius measured to be too large by those amounts. The results for either site are probably within that possible error, although the noise in this determination is somewhat higher than the difference we are looking for. The very low value for the Mount Wilson data nearest the limb also has a relatively large error bar. It should be noted that the model results indicate that the error in the rotation rate should not change very rapidly with CMD, nor does it depend significantly on latitude within the sunspot belt nor on B_0. Furthermore, the percentage error in the derived rotation rate is nearly equal to that in the radius for small values of CMD, so, for example, in the 0.1% modelled result shown in Figure 5, the 'true' rotation rate is 14.436 deg day^{-1},

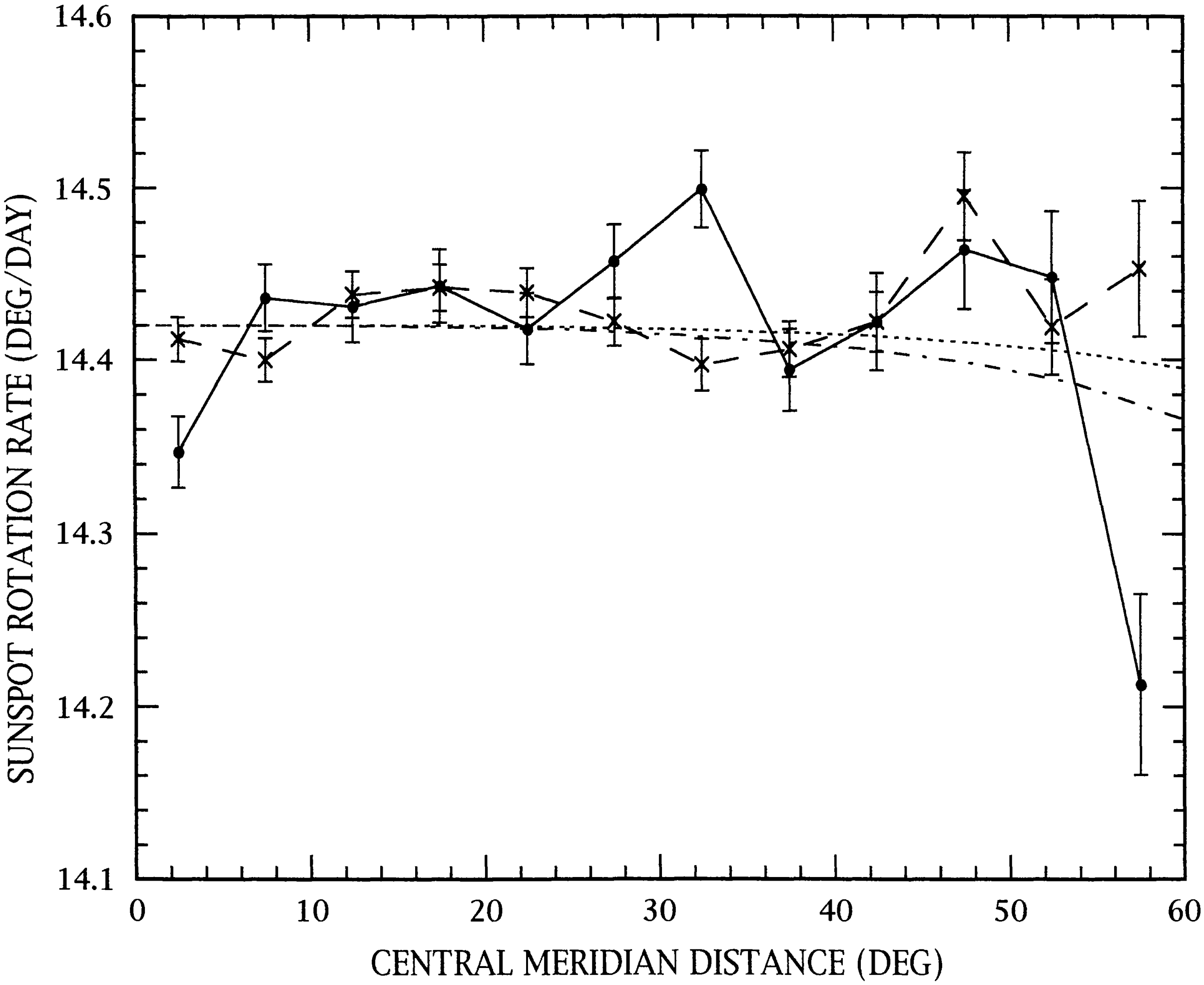

Fig. 5. Average rotation rates averaged over 5-deg intervals of CMD. Circles and solid lines represent the 35-year Mount Wilson data set, and the ×'s and dashed lines represent the same years in the Kodaikanal data. Also shown are the results of model calculations of rotation rates for the cases where the measured radius is too large by 0.1% (upper dot-dashed curve) and by 0.2% (lower dot-dashed curve). Only spots with areas less than 1 μhemisphere and CMDs greater than −45 deg (to avoid rotating beyond the 60-deg limit for measurements) were used here. There are 29557 Kodaikanal spots and 18919 Mount Wilson spots included in this calculation.

although the low-CMD value is 14.2 – and averaging all values would lead to a lower average than that.

Yet another potential source of error in rotation determinations is the image distortion that results from the projection from the celestial sphere to the plane of the photographic plate in a telescope system with a finite focal length (Smart, 1977). The difference in these effects between two systems with different focal lengths can, in principle, lead to systematic positional errors. However, the magnitude of these errors for the focal lengths of the instruments used for these observations ($\approx$ 0.003%) lies more than an order of magnitude lower than the small differences we find.

We should point out that a factor that will tend to make the rotation rate from the combined data set faster is the fact that the combined data set will include more small spots than will the data set from either site, because the smaller spots have shorter lifetimes, and with only a 12-hour time difference between observations, more of these small spots will be observed to 'return'.

Furthermore, differential (with latitude) rotation results may be expected to be affected by the rotation rate-spot size relationship because of possible differences in spot size or in the visibility of smaller spots with latitude. This may be the cause of the difference in the coefficient B between the Mount Wilson and Kodaikanal results given above. The larger (absolute) value for Kodaikanal data suggests that there is a greater falloff of visibility of small spots with latitude in these data. This hypothesis is supported by the finding that there is a much greater discrepancy in average spot areas between the two sites at high latitudes than at low latitudes.

As a test of this hypothesis, Figure 6 shows $residual$ rotation velocities of spots from both sites. The residual rotational velocity is the rotational velocity of a spot minus the average rotational velocity of all spots for that latitude. This eliminates the latitude effect in the rotation analysis. In this plot, which is similar to Figure 4, there is no difference between the size dependence of the rotation rates for the two sites, except for the smallest spots.

In addition, when differential rotation for the two sites is calculated only for spots with areas greater than 5 μhemisphere, it is found that the values of B are not significantly different. They are -2.58 ± 0.04 for 10603 Mount Wilson spots and -2.65 ± 0.05 for 13079 Kodaikanal spots. The value of A derived in this experiment is significantly reduced (about 14.4). The rather low value of B found in this study for the combined data set is puzzling, and cannot be explained easily by discrepancies in spot sizes. This effect will be examined in more detail in a later study.

Altogether, this distribution of possible rotation rate errors should be a caution to those who are tempted to trust any rotation rate determinations (tracer, Doppler, or helioseismic) to one or two tenths of a percent. At this level of precision the results are sensitive to a large array of possible systematic errors.

8. Summary and Conclusions

We may draw the following conclusions from this study:

(1) The agreement between the measured sunspot positions and rotation rates derived from measurements of Kodaikanal and Mount Wilson white-light photographs is generally quite satisfactory.

(2) Combining the two data sets gives significantly more sunspot next-day 'returns' than are derived from any one site.

(3) The differences in overall relative area distributions may be explained partly by the fact that the Kodaikanal image scale is larger than that of the Mount Wilson plates and partly by random selection differences because of different weather patterns at the two sites.

(4) Small ($\approx$ 0.4%) deviations in the average measured rotation rates of

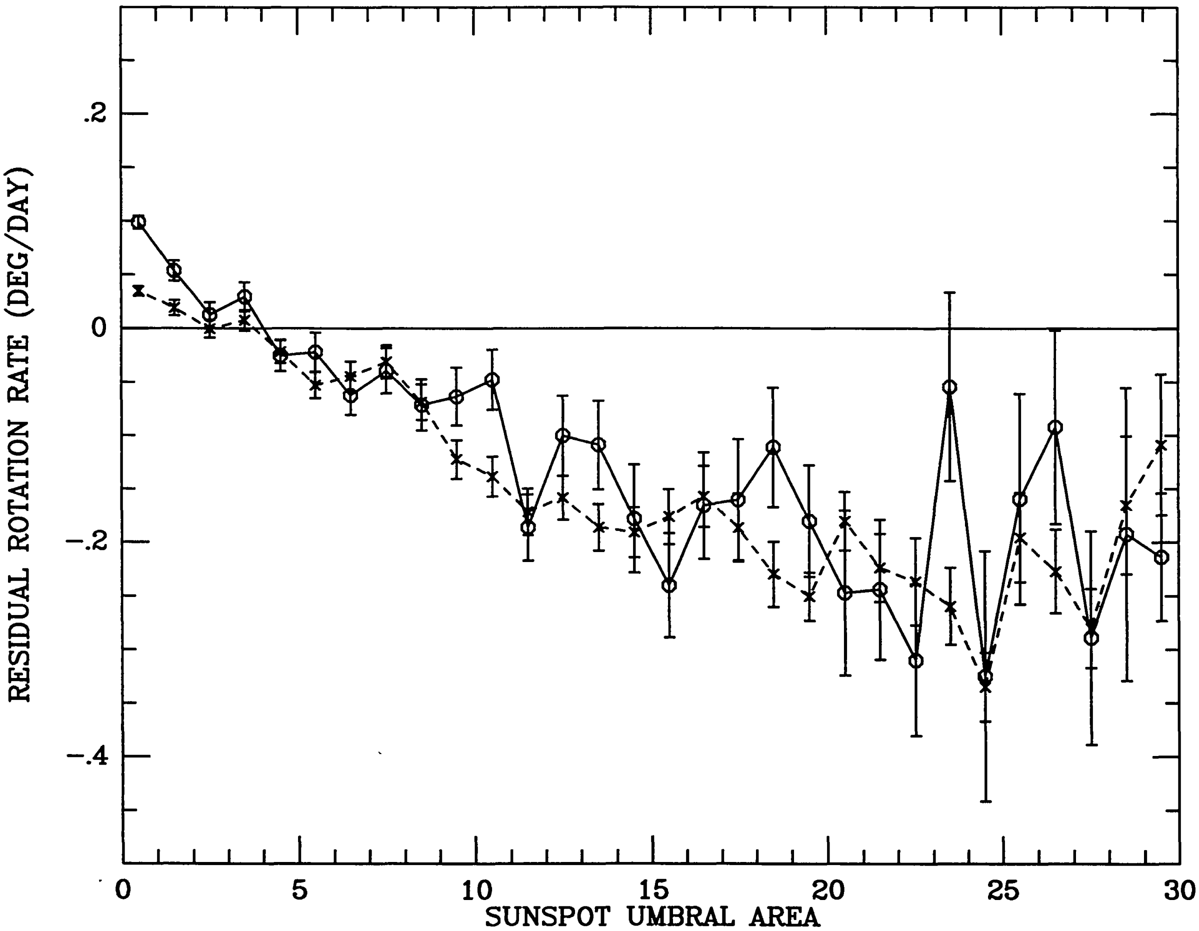

Fig. 6. Similar to Figure 4 except the ordinate is the residual rotation velocity for each site (solid = Mount Wilson; dashed = Kodaikanal). The residual rotation velocity of a spot is the rotation rate of the spot minus the rotation rate of all spots for that latitude.

sunspots from the two sites are detected and are demonstrated to be due in part to differences in the numbers of small spots measured at the two sites.

(5) Errors in the determination of the radius of the Sun can also affect the derived rotation rates, but this effect does not appear to have a large influence on these results.

(6) The latitude dependence of the derived rotation rate is shown to be sensitive to the presence of small sunspots, which rotate faster than larger spots, and whose distribution with latitude is visibility sensitive.

(7) In general, there are a number of subtle systematic differences that can affect rotation results at the level of 0.1%.

One purpose in measuring the Kodaikanal data set is to compare various parameters with previous results from the Mount Wilson data. Another purpose is to combine the two data sets to obtain a larger and more complete data set. For both these purposes it is necessary to have data from the two sites that are sufficiently similar to be comparable and compatible. This study demonstrates that we have achieved that goal for spot areas and for spot rotation rates, at least to the level of a few tenths of a percent.

The spot rotation comparisons suggest that for high precision measurements, one should be very careful about subtle, systematic effects. A similar conclusion was reached in the earlier work (HGG) resulting from the discovery of the effects of small, systematic errors in image orientation on derived meridional flow rates.

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